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LIFE CYCLE MANAGEMENT (LCM)

Life cycle cost analysis of the UK housing stock

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Abstract
Purpose The aim of the paper is to estimate life cycle costs (LCC) of the current housing stock in the UK as part of sustainability assessment of the residential construction sector. This is carried out by first estimating the life cycle costs of individual houses considering detached, semi-detached and terraced homes. These results are then extrapolated to the UK housing stock consisting of seven million each of semi-detached and terraced houses and four million of detached houses. A brief discussion of life cycle environmental impacts is also included to help identify improvement opportunities for both costs and impacts.
Methods The life cycle costing methodology followed in the study is congruent with the life cycle assessment methodology. The system boundary for the study is from 'cradle to grave', including all activities from extraction and manufacture of construction materials to construction and use of the house to its demolition. The functional unit is defined as the construction and occupation of a house in the UK over the lifetime of 50 years.
Results and discussion The total life cycle costs are estimated at £247,000 for the detached house, £192,000 for the semi-detached and £142,000 for the terraced house. The running costs in the use stage contribute 52 % to the total life cycle costs of which half is from energy use. The construction costs contribute 35 % to the total LCC with the walls and the roof being the most expensive items. The remaining 13 % of the costs are incurred at the end of life of the house which are largely (85 %) due to the cost of labour for demolition. Recovery of end-of-life materials has a limited potential to reduce the overall life cycle costs of a house. The life cycle costs of the whole housing stock are estimated at £67 billion per year or £3,360 billion over the 50-year lifetime.
Conclusions The existing housing stock in the UK is facing a number of challenges that will need to be addressed in the near future. These include improving energy efficiency and reducing the dependency on fossil fuels to reduce energy demand, fuel poverty and environmental impacts. Furthermore, the disparity between the construction costs and house market prices will need to be addressed to ensure that access to housing and house ownership do not become the privilege of a few.

Keywords Environmental impacts · Fuel poverty · House costs · Life cycle costs · Residential construction sector · UK houses

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1 Introduction

A number of studies have considered life cycle environmental impacts from the housing sector (e.g. Adalberth 1997; Adalberth et al. 2001; Peuportier 2001; Asif et al. 2007; Hacker et al. 2008; Hammond and Jones 2008; Bribián et al. 2009; Ortiz et al. 2009; Monahan and Powell 2011; Cuéllar-Franca and Azapagic 2012) but the life cycle costs have seldom been addressed. And yet, economic aspects such as housing costs and affordability are important for sustainable development of the residential construction sector.

The housing sector is very important for the UK economy as it directly affects the economic growth (HC 2008). For example, in 2010, the construction industry contributed 8.5 % of the UK's total gross domestic product (GDP) of £1.45 trillion, to which the residential sector contributed 40 % (UKCG 2009). After Denmark and Greece, the UK

has the highest housing prices across the European Union with people spending around 40 % of their income on housing costs such as mortgage payments and energy bills (Eurostat 2012). The latter is the cause of fuel poverty of around six million households owing to the rising energy prices (DECC 2009; Bolton 2010).

In recent years, many people have been unable to purchase a home because of changes in the availability and types of financial and mortgage products (Sergeant 2011; DCLG 2012; RICS 2012). This situation has created an unstable housing market which has led to a fall in house prices and dragged the UK economy further into recession. For example, the average house price in 2008 of around £190,000 fell to £160,000 in 2011 (HPUK 2012). Home ownership is also declining and in 2011 it dropped to 66 from 70.9 % in 2003 so that the proportion of households that own their own homes has fallen back to where it was in 1989 (BBC 2012). This trend is expected to continue over the next 10 years (Sergeant 2011). Such situation is affecting particularly young people—only 10 % of all owner occupiers are under 35 years of age (BBC 2012) while 33 % of first-time buyers are over 35 (DCLG 2012).

It is therefore important to understand the full costs of housing and their main sources along the whole supply chain. This is the subject of this paper which sets out to estimate the life cycle costs (LCC) of the current housing stock in the UK and identify cost reduction opportunities. Three typical types of house are considered: detached, semi-detached and terraced houses (Utley and Shorrock 2008). This work complements a previous study on life cycle environmental impacts of the current housing stock in the UK (Cuéllar-Franca and Azapagic 2012) which are also briefly discussed later in the paper as part of an improvement analysis. As far as the authors are aware, this is the first LCC study of the housing sector in the UK. Elsewhere, only two LCC studies of individual houses have been found in literature, one based in Finland (Hasan et al. 2008) and another in the USA (Keoleian et al. 2000).

2 Methodology

As there is no detailed LCC methodology for the residential construction sector, the methodology used here represents a combination of the general guidelines available for the building sector such as the ISO 15686-5 (BS 2012) and EN 15643-4 (BS 2008) and the approaches described in Swarr et al. (2011), Gluch and Baumann (2004), Hasan et al. (2008), Rebitzer et al. (2003), Abeysundra et al. (2007) and Hunkeler et al. (2007). As far as possible, the LCC methodology adopted here is congruent with the life cycle assessment methodology (ISO 2006a, b).

2.1 Goal and scope

The goal of the study is to assess the life cycle costs of the current housing stock in the UK and identify opportunities for improvements. This is carried out by first estimating the life cycle costs of individual houses considering detached, semi-detached and terraced homes. These results are then extrapolated to the UK housing stock consisting of seven million each of semi-detached and terraced houses and four million of detached homes (Utley and Shorrock 2008). Collectively, this represents 72 % of over 25 million residencies with the rest being apartments in multi-storey buildings, consideration of which is outside the scope of this study.

As indicated in Fig. 1, the system boundary for the study is from ‘cradle to grave’, including all activities from extraction and manufacture of construction materials to construction and operation of the house to its demolition. The functional unit is defined as the construction and occupation of a house in the UK over the lifetime of 50 years. The following typical usable floor areas are considered (Brinkley 2008):

- detached house: 130 m^2;
- semi-detached house: 90 m^2; and
- terraced house: 60 m^2.

Like the large majority of UK houses (92 %), they are assumed to be built in a traditional way, with strip footing foundations, brick external walls and pitched roofs with concrete tiles (Brinkley 2008; DCLG 2008). The average usable floor area across all three types of house is equal to 93 m^2 which compares well with the average 91 m^2 for all UK houses (DCLG 2008). It is also assumed that each house is occupied by an average UK household consisting of 2.3 people (Utley and Shorrock 2008). Therefore, the houses considered in this work are representative of the whole UK housing sector.

Each house has two floors (ground and first floor) and the layout is similar: the kitchen and living area are on the ground floor with the bathroom and the bedrooms on the first floor. Further information on the houses under study can be found in Tables 1 and 2 as well as in Cuellar-Franca and Azapagic (2012).

2.2 Calculation of life cycle costs

The total life cycle costs of a house comprise the costs of construction, use and end-of life-waste management and are calculated as follows:

$$LCC = C_C + C_U + C_{\mathrm{EoL}} \quad (1)$$

where:

LCC total life cycle costs of a house
C_C costs of house construction

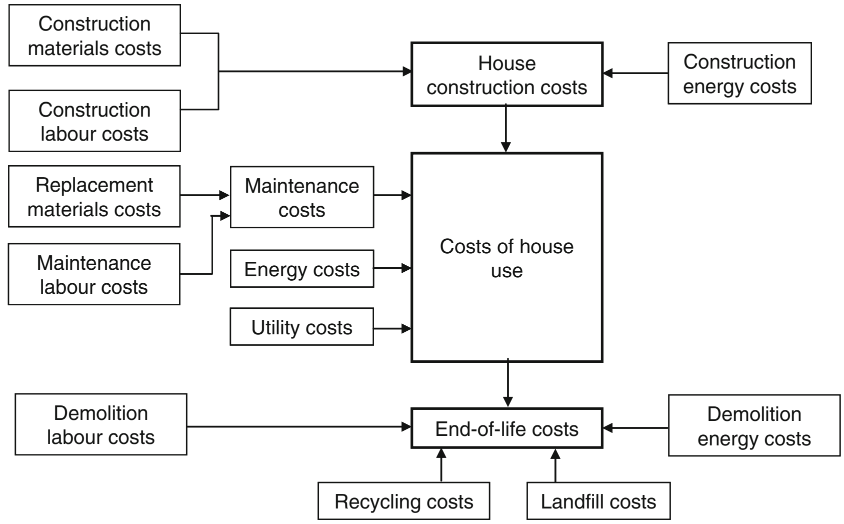

Fig. 1 System boundaries and the costs in the life cycle of the houses considered in the study

C_U costs in the use stage of the house
C_{EoL} costs of end-of-life of the house

The construction costs C_C comprise the costs of the production and transport of construction materials as well as the labour and energy costs for the construction of the house and developer's profits:

$$C_C = C_{\mathrm{CM\&}T} + C_{L\mathrm{\&OH}} + C_{\mathrm{MF}} + P_D \quad (2)$$

where:

$C_{\mathrm{CM\&}T}$ costs of extraction, production and transport of construction materials
$C_{L\mathrm{\&OH}}$ labour and overhead costs
C_{MF} fuel costs for the machinery used in the construction of the house
P_D developer's profits

The costs incurred in the use stage comprise the costs of energy for space and water heating, lighting, cooking and domestic appliances as well as the costs for water and waste water treatment. Maintenance costs during its service life are also considered and include cost of labour, materials, energy and transport associated with the replacement of windows, doors and floor covering:

$$C_U = C_E + C_W + C_M \quad (3)$$

where:

C_E costs of energy
C_W costs of water and waste water
C_M costs of maintenance

Finally, end-of-life includes costs of labour and energy (fuel) for demolishing a house, waste collection services and transport costs as well as waste management costs such as landfilling and recycling of construction waste:

$$C_{\mathrm{EoL}} = C_{\mathrm{DL}} + C_{\mathrm{DF}} + C_{\mathrm{WC}} + C_{\mathrm{WT}} + C_{\mathrm{LF}} + C_{\mathrm{REC}} \quad (4)$$

where:

C_{DL} costs of labour for demolishing the house
C_{DF} costs of fuel for the demolition machinery
C_{WC} costs of collection of demolition waste
C_{WT} costs of transport of demolition waste
C_{LF} costs of waste landfilling
C_{REC} costs of waste recycling

Table 1 General information on the houses under study

	Detached house	Semi-detached house	Terraced house	Source
Usable floor area (m^2)	130	90	60	Brinkley (2008)
Household size (no. of people)	2.3	2.3	2.3	Utley and Shorrock (2008)
Number of bedrooms	4	3	2	Utley and Shorrock (2008)
Number of floors	2	2	2	BTP (2010)
Construction type	Traditional build: brick and block	Traditional build: brick and block	Traditional build: brick and block	BTP (2010)
Indoor temperature (°C)	19	19	19	Utley and Shorrock (2008); Brinkley (2008)
Air exchange rate (h^{-1})	1	1	1	Brinkley (2008)
Specific heat loss (W/K)	220	170	120	Brinkley (2008); BTP (2010)

Table 2 Materials used for the construction of houses[a]

Element	Surface (m²)			Components	Thickness (mm)	Amount (kg)		
	Detached	Semi-detached	Terraced			Detached	Semi-detached	Terraced
External wall	194	141	90	Brick (Imperial 9″), outer leaf	102.5	43,828	31,747	20,193
				Cement mortar	10	11,662	8,447	5,373
				Extruded polystyrene	75	510	292	96
				Concrete block (aerated), inner leaf	100	14,577	10,559	6,716
				Plasterboard	12.5	1,944	1,408	895
				Gypsum plaster skimming	3	653	473	301
Internal wall	99	85	44	Brick (Imperial 9″), inner leaf	102.5	22,302	19,199	9,809
				Cement mortar	10	5,934	5,108	2,610
				Plasterboard	12.5	1,978	1,703	870
				Gypsum plaster skimming	3	665	572	292
Foundation	30	25	19	Brick (Imperial 9″)	–	16,144	13,362	10,956
				Cement mortar	–	1,044	870	726
				Concrete	–	19,615	16,157	13,094
Ground floor	62	43	28	Cement mortar	20	190	233	173
Ceiling and first floor	4.4	5.4	4	Timber floor boards	20	640	443	288
Bathroom and bedrooms	58	39	24	Carpet (bedrooms)	–	30	21	12
				Ceramic floor tiles (bathroom)	–	70	86	64
				Mineral wool	200	236	163	106
				Softwood timber (main beams and joists)	–	1,104	767	504
				Plasterboard	12.5	621	430	280
				Gypsum plaster skimming	3	209	144	94
Ground floor	65	45	30	Ceramic floor tiles (kitchen/toilet)	–	303	162	84
Kitchen, toilet and living room	25	10	5	Cement mortar	20	822	438	227
	40	35	25	Laminated floor (living room)	–	264	227	161
				Concrete slab	100	15,600	10,824	7,200
				Expanded polystyrene	100	150	104	69
				Damp-proof membrane	–	16	11	8
				Sand and gravel	50	7,280	5,051	3,360
Roof (timber structure)	75	52	35	Concrete tiles	–	3,750	2,602	1,732
	81	54	38	Sarking felt	–	9	7	4
				Softwood timber (purlins, ridge and wall plates, rafter, battens and truss membranes)	–	2,478	1,668	1,185
First floor ceiling	65	45	30	Softwood timber (joists)	–	78	54	38
				Mineral wool	300	449	311	207
				Plasterboard	12.5	650	451	300
				Gypsum plaster skimming	3	218	152	101
Windows	13	10	8	U-PVC frame	–	254	207	167
				Double glazed panes	–	197	160	129
Interior doors	11	9	6	Hardwood timber	34	292	250	167
Exterior doors	3	3	3	Hardwood timber	44	121	121	121
				Total materials (kg)		**176,931**	**134,965**	**88,701**

[a] Data source: Cuéllar-Franca and Azapagic (2012)

Bold as it represents the total of all of the above items in the table

In addition to the costs, there will be some revenue from selling the construction waste for reuse and/or recycling for which the system should be credited. However, due to a lack of data, this is excluded from the study but it is considered as part of the sensitivity analysis further in the paper.

All the costs represent 'overnight' costs, i.e. as if incurred at present time for all the life cycle stages so that no discounting is applied (BS 2008, 2012). This is for two reasons. First, the economic performance of the houses is expressed in cost rather than financial-value terms. Secondly, one of the aims of the paper is to identify cost hot spots in the life cycle of houses and related improvements which would be applicable and carried out in the present time rather than in the future. However, the influence of more volatile costs such as energy on the total

Table 3 Costs of house construction (in UK Pounds)[a]

Activities/elements/components	Detached house				Semi-detached house				Terraced house			
	Materials	Labour	Fuel and machinery	Profit	Materials	Labour	Fuel and machinery	Profit	Materials	Labour	Fuel and machinery	Profit
Construction activities			**564**				**390**				**260**	
External wall	**13,050**	**18,733**		**3,178**	**9,568**	**13,733**		**2,330**	**6,244**	**8,959**		**1,520**
Brick (Imperial 9″) and cement mortar	7,230	8,916		1,615	5,255	6,480		1,174	3,354	4,136		749
Extruded polystyrene	1,847	1,098		294	1,342	798		214	857	509		137
Concrete block	3,104	5,962		907	2,256	4,333		659	1,440	2,766		421
Plasterboard	704	993		170	595	840		143	516	729		125
Gypsum plaster skimming	165	1,763		193	120	1,282		140	77	818		89
Internal wall	**4,673**	**7,202**		**1,187**	**3,911**	**6,041**		**995**	**2,012**	**3,109**		**512**
Brick (Imperial 9″) and cement mortar	3,690	4,550		824	3,168	3,907		707	1,640	2,022		366
Plasterboard	899	1,269		217	671	947		162	335	472		81
Gypsum plaster skimming	84	1,383		147	72	1,187		126	37	615		65
Foundation	**1,577**	**1,636**		**321**	**1,396**	**1,433**		**283**	**1,137**	**1,169**		**231**
Double brickwork and cement mortar	732	899		163	606	744		135	497	610		111
Concrete	846	737		158	791	689		148	641	558		120
First floor	**3,260**	**5,130**		**839**	**2,423**	**3,880**		**630**	**1,508**	**2,440**		**395**
Carpet (polypropylene)	577	919		150	390	621		101	238	382		62
Ceramic floor tiles and cement mortar (bathroom)	126	337		46	155	413		57	115	306		42
Timber floor boards (softwood)	1,009	1,036		205	698	717		142	455	467		92
Mineral wool	530	287		82	367	199		57	238	129		37
Joists (100×50 mm)–softwood timber	7	13		2	4	7		1	4	7		1
Main beams (200×50 mm)–softwood timber	767	1,161		193	641	970		161	349	529		88
Plasterboard	192	247		44	133	171		30	87	111		20
Gypsum plaster skimming	53	1,129		118	37	782		82	24	509		53
Ground floor	**2,433**	**5,050**		**748**	**1,605**	**3,384**		**499**	**1,027**	**2,197**		**322**
Ceramic floor tiles and cement mortar (Kitchen/ Toilet)	544	1,455		200	286	766		105	143	383		53
Laminated floor (Oak)	147	1,892		204	112	1,440		155	80	1,029		111
Concrete slab	700	1,016		172	484	704		119	323	469		79
Expanded Polystyrene	641	686		133	444	475		92	296	317		61
DP membrane (polypropylene)	30	0		3	21	0		2	14	0		1
Sand	186	0		19	129	0		13	86	0		9
Gravel	186	0		19	129	0		13	86	0		9
Roof	**7,570**	**7,969**	**116**	**1,554**	**5,077**	**5,137**	**81**	**1,021**	**3,568**	**3,700**	**54**	**727**
Concrete tiles	3,819	2,695		651	2,648	1,868		452	1,782	1,258		304
Sarking felt	1,289	1,537	116	283	894	1,065	81	196	602	717	54	132
Purlins (75×225 mm)	170	129		30	94	71		16	68	51		12
Ridge plate (50×100 mm)	19	44		6	10	24		3	8	18		3
Wall plates (75×100 mm)	57	88		14	31	48		8	23	35		6

Table 3 (continued)

Activities/elements/components	Detached house				Semi-detached house				Terraced house			
	Materials	Labour	Fuel and machinery	Profit	Materials	Labour	Fuel and machinery	Profit	Materials	Labour	Fuel and machinery	Profit
Rafter (50×100 mm)	326	755		108	227	526		75	162	375		54
Battens (25×38 mm)	281	1,062		134	141	531		67	129	488		62
Truss: Bottom membrane (50×200 mm)	424	655		108	295	456		75	210	325		54
Truss: Internal membrane (50×125 mm)	1,185	1,006		219	737	547		128	584	433		102
Ceiling	**957**	**1,472**		**243**	**663**	**1,019**		**168**	**443**	**682**		**112**
Joists (100×50 mm)–softwood timber	30	69		10	21	48		7	15	34		5
Mineral Wool	671	364		104	465	252		72	310	168		48
Plasterboard	201	258		46	139	179		32	93	119		21
Gypsum plaster skimming	55	781		84	38	541		58	26	361		39
Windows	**452**	**742**		**119**	**359**	**592**		**95**	**245**	**402**		**65**
Bedroom window (1.1 m×1.8 m)	268	444		71	201	333		53	134	222		36
Living room window (1.35 m×1.6 m)	73	121		19	73	121		19	73	121		19
Kitchen window (1.1 m×1.6 m)	59	99		16	59	99		16	12	20		3
Bathroom window (0.5 m×0.7 m)	52	78		13	26	39		7	26	39		7
Interior doors	**298**	**300**		**60**	**255**	**257**		**51**	**170**	**171**		**34**
Exterior doors	**348**	**120**		**47**	**348**	**120**		**47**	**348**	**120**		**47**
Total	**34,618**	**48,354**	**680**	**8,364**[b]	**25,605**	**35,596**	**471**	**6,176**[b]	**16,702**	**22,949**	**314**	**3,996**[b]

[a] Data sources: Hutchins (2010) and BBC (2011)

[b] Includes 10 % profit for the total costs for the fuel and machinery

Bold as it represents the total of all of the above items in the table

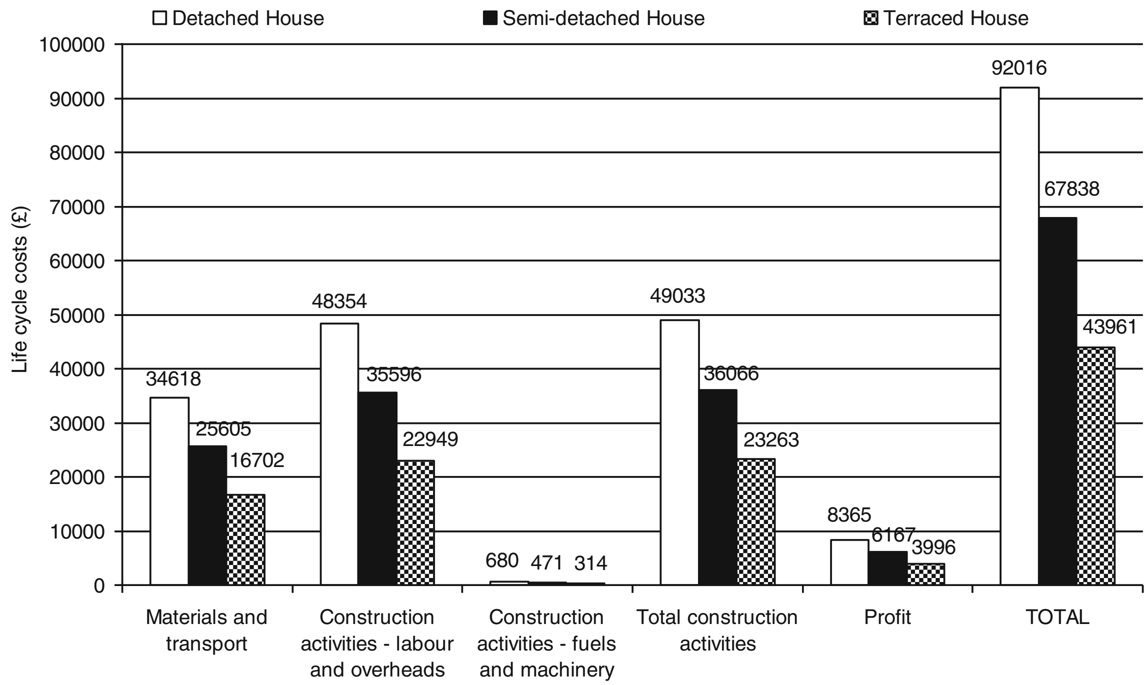

Fig. 2 Life cycle costs for the construction stage

LCC is analysed as part of the sensitivity analysis as suggested by ISO 15686-5 (BS 2008).

3 Life cycle costs of individual houses

The cost estimations for each life cycle stage are based on the data in Tables 2 and 3. The total costs are assessed from the supply chain perspective while the costs in each stage are estimated based on the perspective of the key player in that stage. The following section provides an overview of the costs by life cycle stage, followed by the overall life cycle costs in Section 3.2 and costs per floor area in Section 3.3. Note that the costs discussed below have been rounded off; the actual estimated values can be found in the corresponding figures and tables.

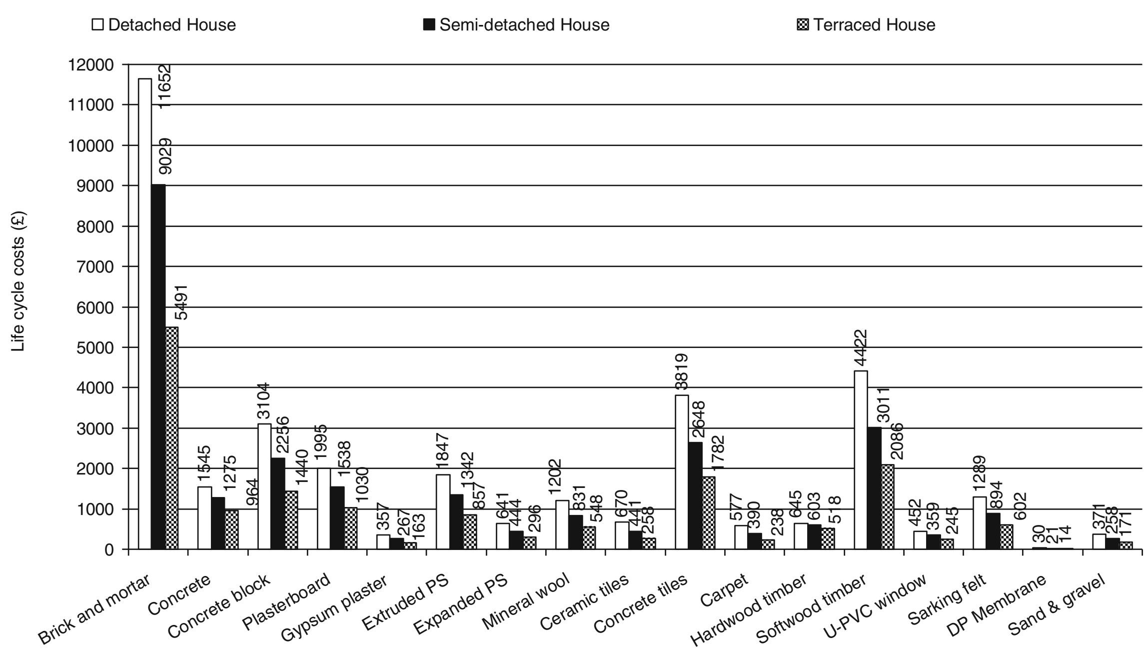

Fig. 3 Life cycle costs of construction materials

Table 4 Energy consumption for the three types of house over 50 years (in megajoule)[a]

Life cycle stage		Detached house	Semi-detached house	Terraced house
Construction	*On-site construction*	*31,200*	*21,600*	*14,400*
Use	Space heating	2,820,000	2,160,000	1,602,000
	Water heating[b]	912,500	912,500	912,500
	Cooking[b]	103,500	103,500	103,500
	Lighting	255,750	151,150	93,700
	Appliances[b]	314,360	314,360	314,360
	Use total	*4,406,110*	*3,641,510*	*3,026,060*
End-of-life	*Demolition*	*14,500*	*1,000*	*6,700*
	Total	**4,451,810**	**3,673,110**	**3,047,160**

[a] Data source: Cuéllar-Franca and Azapagic (2012)

[b] Note that the amount of energy used for water heating, cooking and appliances is the same for all three types of house as these activities depend on the number of occupants which is equal for all three types

Italicised figures represent sub-totals

Bold as it represents the total of all of the above items in the table

3.1 Costs by life cycle stage

3.1.1 Construction stage

The costs in this stage refer to the costs to the construction company or developer. The costs of construction materials and their transport as well as of energy and labour have been sourced from a construction cost guide for the UK (Hutchins 2010). Land costs are excluded from the study as these are highly variable, depending on the location and land ownership models. This is also congruent with the recommendations in ISO 15686-5 (BS 2008).

As detailed in Table 3 and summarised in Fig. 2, the total construction costs are estimated at around £92,000 for the detached, £67,800 for the semi-detached and £44,000 for the terraced house, including a 10 % profit for the construction company (Hutchins 2010). The main contributors to the costs are the construction labour (52 %) and materials (35 %). The former are estimated at around £48,000, £35,600 and £23,000 respectively, including a 20 % overhead (Hutchins 2010). The costs of the construction materials are £34,600 for the detached, £25,600 for the semi-detached and £16,700 for the terraced house. These costs include labour for the extraction and manufacture of the materials as well as the costs of transportation to the construction site. The breakdown for the materials costs can be seen in Fig. 3.

As can also be seen from Fig. 2, the total cost of fuels and machinery hire are small by comparison: £680 for the construction of the detached house, £470 for the semi-detached and £310 for the terraced house.

3.1.2 Use stage

The costs in the use stage are considered from the home owner/occupier perspective. These include the cost of energy for space and water heating, cooking, lighting and the use of domestic appliances (see Table 4). The energy consumption figures are based on the house floor area and household size defined in Section 2.1. The energy for space heating also takes into account the specific heat loss for each house, following the method suggested in Brinkley (2008). Water heating estimations are based on the water heating figures for the residential sector reported in Utley and Shorrock (2008), assuming a daily domestic hot water consumption of 76.5 l per person (DCLG 2010). The figures for cooking are derived from Utley and Shorrock (2008) and those for appliances and

Table 5 Breakdown of water consumption per house over 50 years (Defra 2010; MTP 2008; VADO 2010)[a]

Activities	End use (%)	Volume used (m^3)	Volume discharged (m^3)
Personal hygiene	30	1,890	1,890
W.C.	30	1,890	1,890
Washing machine/dishwasher	21	1,320	1,320
Housekeeping	8	500	500
Personal consumption	4	250	0
Gardening	4	250	250
Others	3	200	200
Total	**100**	**6,300**	**6,050**

[a] Note that the total water consumption is equal for all three types of house as the number of occupants is the same

Bold as it represents the total of all of the above items in the table

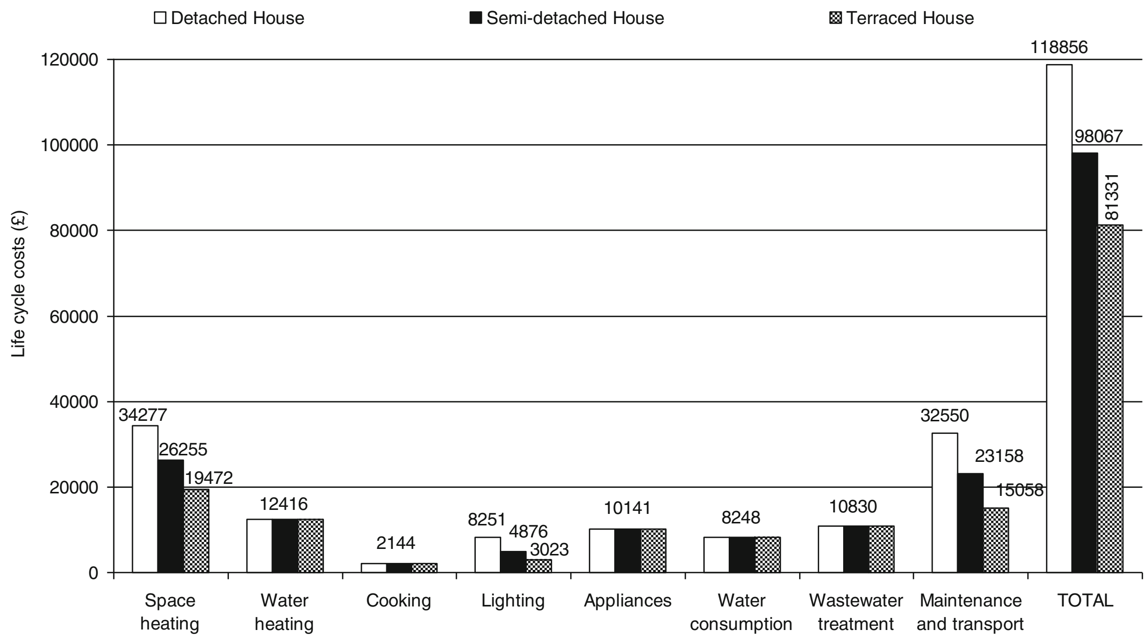

Fig. 4 Life cycle costs in the use stage

lighting are based on the figures reported in Baker and Jenkins (2007). Based on these figures, the total energy consumed over the lifetime of the houses ranges from 3.05 TJ for the terraced to 4.45 TJ for the detached house (see Table 4).

The breakdown of the costs associated with water consumption and discharge can be found in Table 5. Assuming an average water consumption of 150 l per day per person (Defra 2010) and the breakdown of water usage by activity (MTP 2008; VADO 2010), the total water consumption is estimated at 6,280 m^3 over the lifetime of the house.

Therefore, the total running costs over the service life of a detached house are equal to £118,900 (Fig. 4). For the semi-detached and terraced, these costs are £98,000 and £81,300, respectively. The main contributors to the costs in this stage are energy consumption for space and water heating (40 %) and maintenance (on average, 23 %).

The total energy costs are between £47,200 and £67,200 (Table 6). This equates to the annual energy bill of £950 for the terraced house and £1,350 for the detached, giving an average energy bill of £1,135. This estimate is comparable to the average energy bill of £1,200 reported by Bolton (2010).

The costs of water use and waste water treatment are estimated at £19,100 or around £380 annually (see Table 6). These costs are the same for all three types of house owing to the same number of occupants which determines the amount of water used (as opposed to energy which, for some types of use, e.g. heating, also depends on the size of the house).

The maintenance costs include replacement costs for carpets (every five years), doors, ceramic and laminate flooring (every 20 years) and windows (25 years). Using the costs for the replacement materials and components given in Table 3, the overall costs of maintenance over the lifetime of the

Table 6 Annual (and lifetime) energy and utility costs in the use stage

Fuel/energy source[a]	Detached house	Semi-detached house	Terraced house
Gas, £/year (£)	684 (34,200)	564 (28,200)	462 (23,100)
Heating oil, £/year (£)	87 (4,350)	71 (3,550)	57 (2,850)
Solid fuels, £/year (£)	13 (650)	11 (550)	8 (400)
Electricity, £/year (£)	560 (28,000)	471 (23,550)	416 (20,800)
Total annual energy costs, £/year (£)	**1,344 (67,200)**	**1,117 (55,850)**	**944 (47,200)**
Water, £/year (£)[b]	165 (8,250)	165 (8,250)	165 (8,250)
Waste water, £/year (£)[b]	217 (10,850)	217 (10,850)	217 (10,850)
Total annual utility costs, £/year (£)	382 (19,100)	382 (19,100)	382 (19,100)

[a] Unit energy prices: gas: £10.84/GJ; oil: £13.67/GJ; solid fuels: £10.13/GJ; electricity: £32.28/GJ (Bolton 2012)

[b] Unit costs of water: £1.31/m^3 ; unit cost of waste water treatment: £1.72/ m^3 (OFWAT 2010)

Bold as it represents the total of all of the above items in the table

Table 7 Total costs of maintenance and repairs over the lifetime of the house (£)

	Detached house	Semi-detached house	Terraced house
Windows	1,693	1,355	1,751
Interior doors	1,459	1,250	1,592
Exterior doors	1,069	1,069	2,041
Floor coverings	28,330	19,483	23,365
Total	**32,550**	**23,158**	**15,059**

Bold as it represents the total of all of the above items in the table

houses are estimated at around £32,550 for the detached house, £23,200 for the semi-detached and £15,100 for the terraced house (Table 7). These include the costs of labour, materials, energy as well as a 10 % profit for the maintenance companies (Hutchins 2010).

3.1.3 End-of-life stage

The costs in this stage are assessed from the perspective of the companies involved in different end-of-life activities such as demolition companies, waste collectors and landfill operators. The end-of-life materials and assumed waste management practices are given in Table 8; the assumed transportation distances for the waste materials are summarised in Table 9.

As shown in Table 10, the total costs of house demolition are around £16,600 for the terraced house, £26,400 for the semi-detached and £36,200 for the detached house. The majority of these (85 %) are due to the labour costs, ranging from £13,700 to £30,500, respectively (Fig. 5). The next highest cost item is waste collection from the demolition site (£2,150–4,300). As indicated in Fig. 5, the cost of fuel used for the demolition and waste disposal costs are small (in the order of several hundred pounds) while the costs of transport of the demolition waste are negligible (tens of pounds).

It should be noted that demolition companies usually offset the costs of demolition by selling construction waste as scrap (SilverCrest 2010). Owing to a lack of data for the prices of recovered materials, it has not been possible to take this into account but a sensitivity analysis has been carried out (later in the paper) to gauge the influence of the sales of second-hand materials on the total LCC costs.

3.2 Total life cycle costs and 'hot spots'

As shown in Fig. 6, the total life cycle cost of a detached house is £247,000, for the semi-detached and terraced houses the equivalent values are £192,000 and £142,000, respectively. The use stage is responsible for the majority (52 %) of the costs, largely from the use of energy. The construction stage contributes 35 %, of which the labour costs contribute more than a half and construction materials around a third. Finally, end-of-life activities are responsible for 13 % of the total costs, owing mainly to the labour costs.

Therefore, these areas should be targeted for reducing the housing life cycle costs. For example, making the existing houses more energy efficient through improved insulation, use of energy-efficient appliances and lighting would reduce energy bills but also environmental impacts since the use stage is also the hot spot for most impact categories (see Fig. 7).

The second highest contributor to the LCC is the cost of construction materials such as bricks and concrete. Since these materials also have high embodied carbon (Cuéllar-Franca and Azapagic 2012), both the costs and climate change impact of future housing stock could be reduced

Table 8 End-of-life waste materials and waste management options

	Reused/recycled/landfilled (%)[a]	Detached house (kg)	Semi-detached house (kg)	Terraced house (kg)
Concrete, binders and aggregates	0/100/0	81,995	61,292	41,809
Bricks	51/36/13	82,281	64,295	40,950
Gypsum	0/100/0	6,939	5,331	3,133
Ceramic tiles	57/7/36	934	619	369
Insulation	18/0/82	1,360	882	485
Other inert waste (carpets, glass etc.)	15/15/70	704	533	388
Timber	2/79/19	6.079	4,428	3,137
U-PVC	0/50/50	507	413	333
Total		**180,799**	**137,793**	**90,604**

[a] Based on current UK waste management practice (Kohler and Davies 2007; CRW 2009). Unit price of diesel for the demolition machinery: £1.33/l (BBC 2011)

Bold as it represents the total of all of the above items in the table

Table 9 Transportation in the life cycle of the three types of house (t.km)[a]

	Detached house	Semi-detached house	Terraced house
Construction	8,400	6,350	4,000
Use (maintenance)	200	120	80
End of life	8,500	6,500	4,200
Total	**17,100**	**12,970**	**8,280**

[a] Data source: Cuéllar-Franca and Azapagic (2012)

Bold as it represents the total of all of the above items in the table

through material substitution but also more energy-efficient house designs. Some examples include timber-frame houses (Brinkley 2008) as well as construction of 'passive' (BRE 2011) and 'zero-carbon' houses (DCLG 2010).

Finally, although the end-of-life costs are mainly due to the labour, demolition costs could be offset by increasing reuse and recycling of construction materials, which at the same time would reduce the amount of waste sent to landfill and related environmental impacts. However, the potential for the latter from end-of-life activities is relatively small as their contribution to the total impacts is not significant (see Fig. 7). Further discussion on cost improvement opportunities at the sectoral level can be found in Section 4.

3.3 Life cycle costs per floor area

This section compares the costs of the three types of house per unit floor area to find out which house design may be more or less expensive overall. As can be observed from Fig. 8, the detached house has the lowest life cycle costs (£1,900/m^2), followed by the semi-detached (£2,140/m^2); the terraced house has the highest costs (£2,400/m^2). These differences are mainly due to the use stage as the construction and end-of-life costs are similar for the three designs. Given the same household size assumed for all three types of house and the fact that the energy used for water heating, cooking and appliances is the same (see Table 4), it is not surprising that the larger floor area (e.g. detached) will have a lower cost per unit area than a smaller one (e.g. terraced).

3.4 Validation of results

As already mentioned, there are no other studies of the LCC of houses in the UK so comparison of the results obtained here with previous studies is not possible. It is also not possible to compare the results obtained here with the studies based in Finland (Hasan et al. 2008) and the USA (Keoleian et al. 2000) because of the different methodologies used as well as different housing costs in these countries compared to the UK. For example, Hasan et al. (2008) do not consider full life cycle costs because their focus is on the cost differential between a reference and several case studies. Keoleian et al. (2000), on the other hand, consider LCC from a homeowner perspective where construction costs are replaced by mortgage payments, rendering a comparison with the current study infeasible.

Table 10 End-of-life costs (in UK Pounds)[a]

	Detached house	Semi-detached house	Terraced house
Demolition energy (fuel)	500	346	231
Demolition labour	30,516	22,389	13,772
Demolition waste collection (incl. labour)[b]	4,306	2,990	2,133
Demolition waste transport (fuel)	64	48	32
Landfilling (incl. labour)[c]	528	400	256
Recycling (incl. labour)[d]	265	196	142
Total	**36,179**	**26,368**	**16,565**

[a] Data sources: Hutchins (2010), SilverCrest (2010), Bolton (2010), OFWAT (2010), CRW (2009), Kohler and Davies (2007), BBC (2011) and Dewulf et al. (2009)

[b] Waste collection costs: £165 per 8 cubic yard skip of waste, including labour costs (SilverCrest 2010)

[c] Landfill disposal cost: £25/t plus £2.50/t inactive waste and £56/t active waste (HMRC 2011). Inactive waste includes bricks, aggregates, glass and mineral wool; active waste includes timber, UPVC and insulation materials

[d] Fuel costs estimated using the fuel type and quantities specified for different machinery in EcoInvent (2011) and corresponding fuel prices (BBC 2011; DECC 2010). Labour costs for recycling estimated based on the time required to process the waste and the capacities of the recycling machinery (crusher, wood chipper and granulator; Zenith 2011; FF 2011; PRC 2011). Operator's wage: £20.85 per hour (Hutchins 2010)

Bold as it represents the total of all of the above items in the table

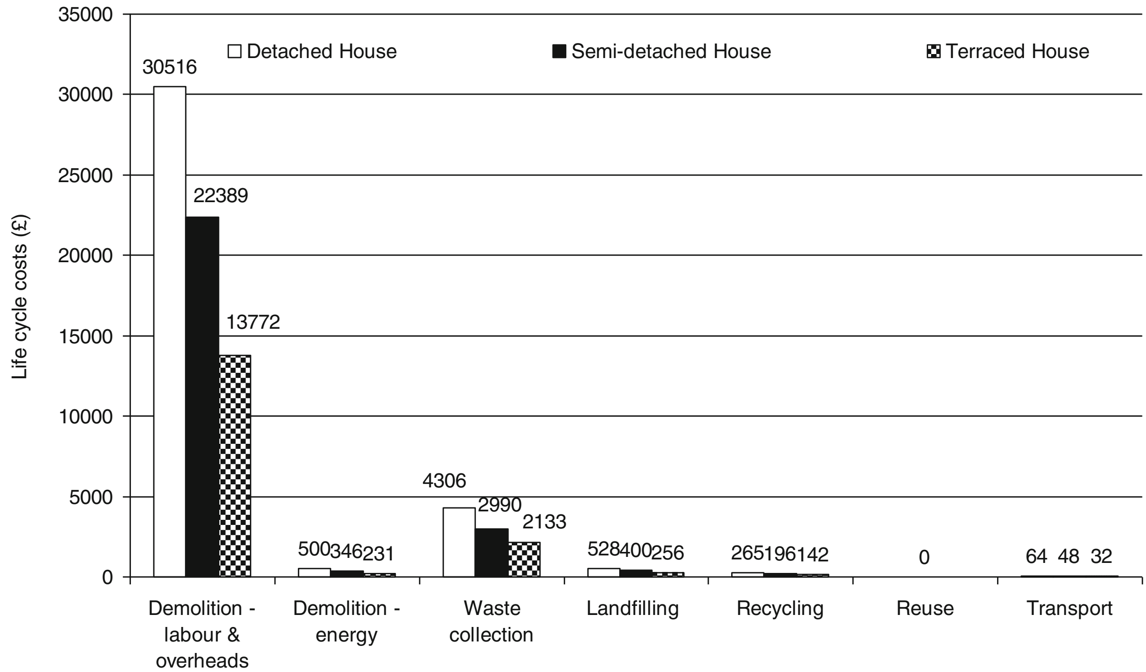

Fig. 5 Life cycle costs of the end-of-life stage including the waste from maintenance

The only data that have been found for the UK are those related to the national statistics for the average household expenditure which was estimated at around £2,600 in 2011 (Halifax 2011). This is compared to the results obtained in this work in Fig. 9. As shown, the results are relatively close (£1,630–2,380), despite the different assumptions and methodologies used.

3.5 Sensitivity analysis

3.5.1 Energy costs

This section considers the effect of potential future energy prices on the life cycle costs of houses. Three scenarios are considered and compared to the reference case. The latter

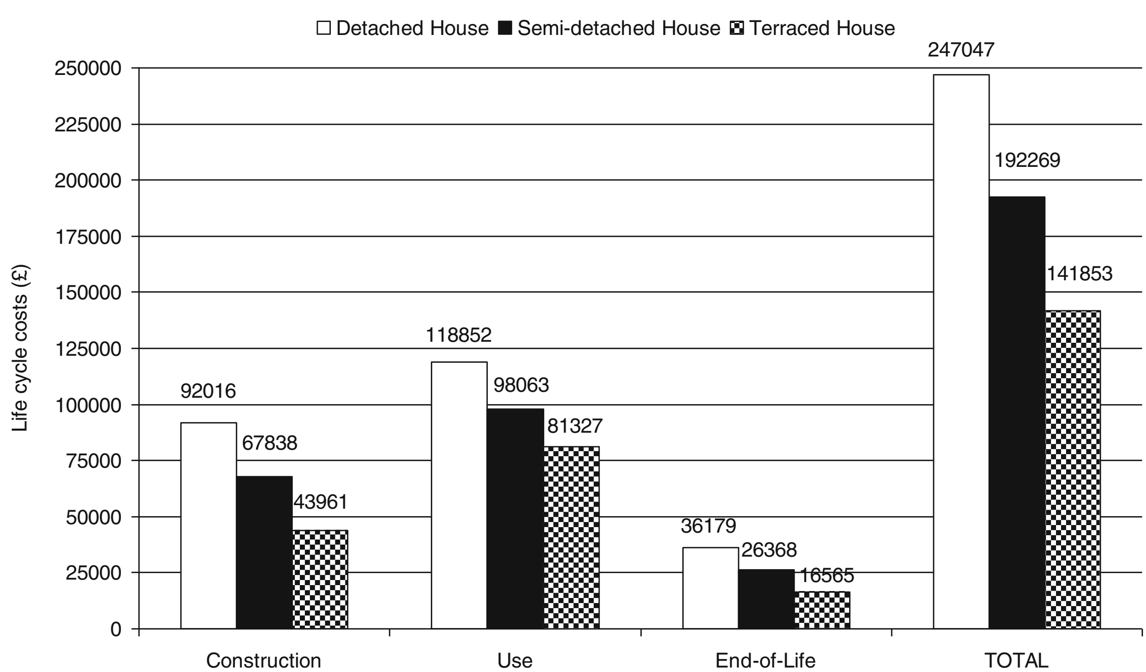

Fig. 6 Total life cycle costs for the detached, semi-detached and terraced houses over the lifetime of 50 years

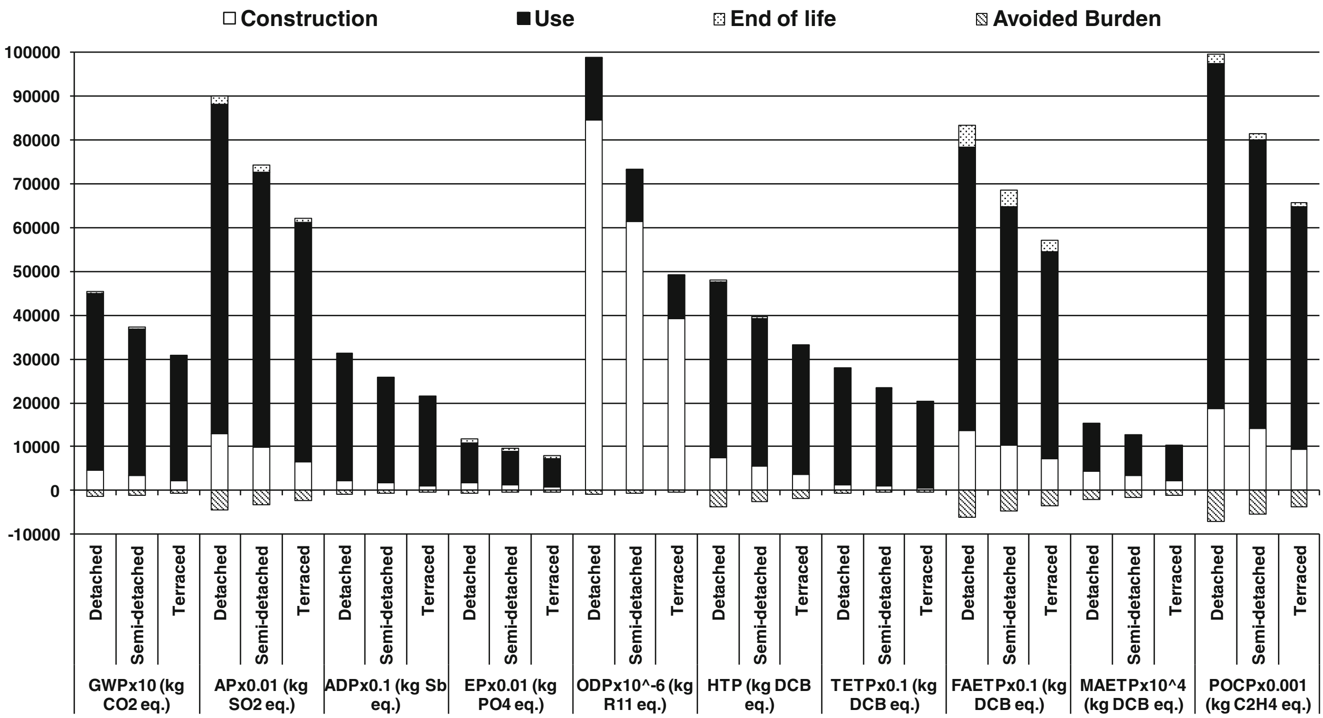

Fig. 7 Total life cycle impacts of the detached, semi-detached and terraced houses over the lifetime of 50 years showing the contribution of different life cycle stages (based on Cuéllar-Franca and Azapagic (2012))

assumes the 2010 energy prices fixed over the 50-year lifetime of the houses, as presented in Section 3.1. Scenarios 1 and 2 assume a fixed annual increase of energy costs over the service life of a house, following the retail price index (RPI). Scenario 1 considers an annual fuel cost increase of 1.7 % corresponding to the RPI between 2009 and 2010 and scenario 2 assumes the increase of 2.5 %, which corresponds to the cost increase between the first quarter of 2010 and first quarter of 2011 (DECC 2011a). In scenario 3, the energy cost increases annually by the average price increase between 2009 and 2011 (DECC 2011a). During this period, gas and electricity prices rose by 3.32 and 1.68 %, respectively, while

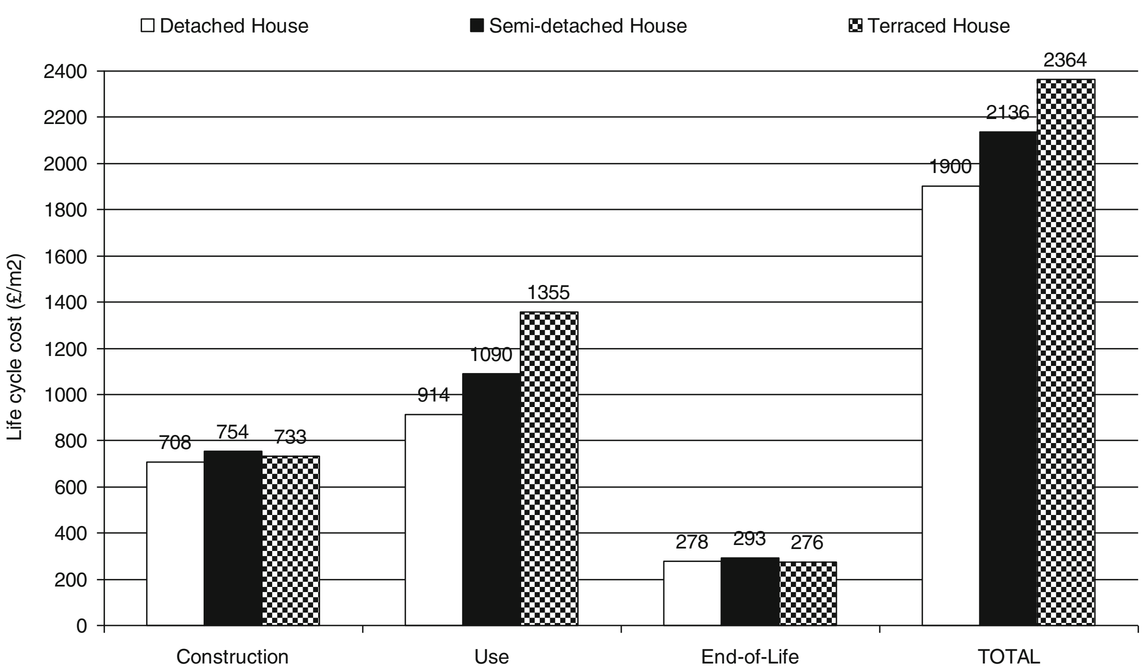

Fig. 8 Comparison of life cycle costs of the detached, semi-detached and terraced houses per unit floor area over 50 years

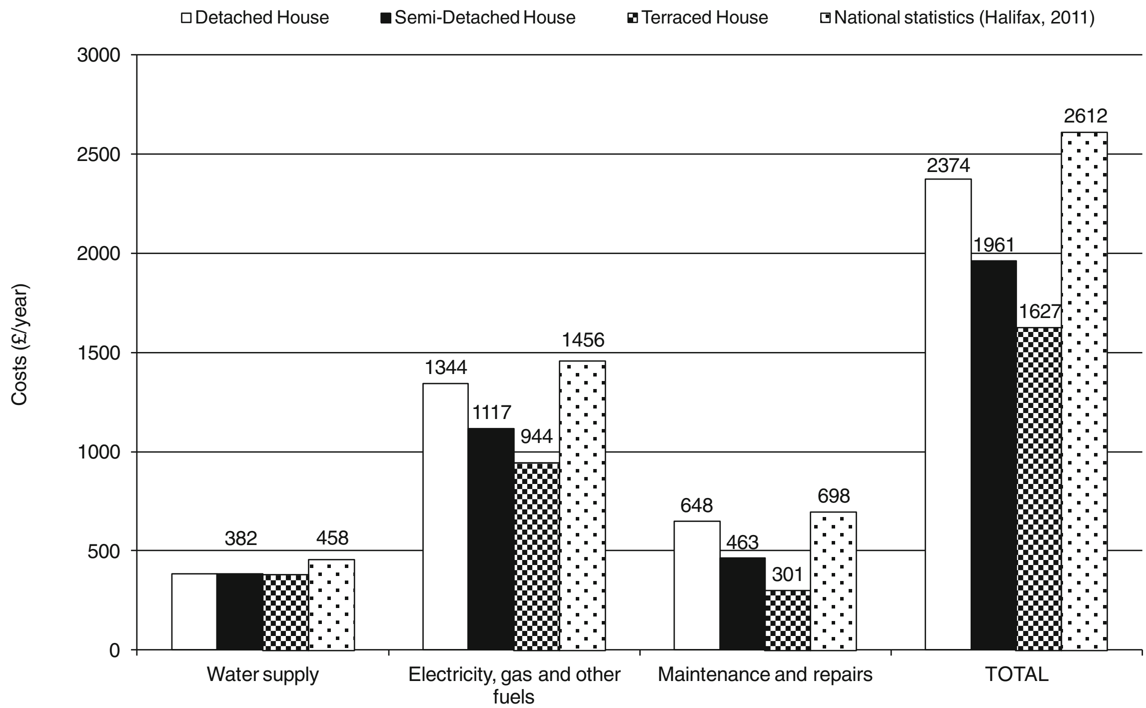

Fig. 9 Validation of the results: comparison of the costs from the use stage with the annual household expenditure

the cost of heating oils and coal increased by 3.83 and 6.12 %, respectively.

The total energy costs for the three types of house are shown in Figs. 10, 11 and 12. As indicated, the costs increase over the lifetime of houses by 55 % in scenario 1, 94 % in scenario 2 and 114 % in scenario 3, compared to the reference case.

Figure 13 shows the annual energy cost increments over the service life of the house for each scenario (for illustration, only

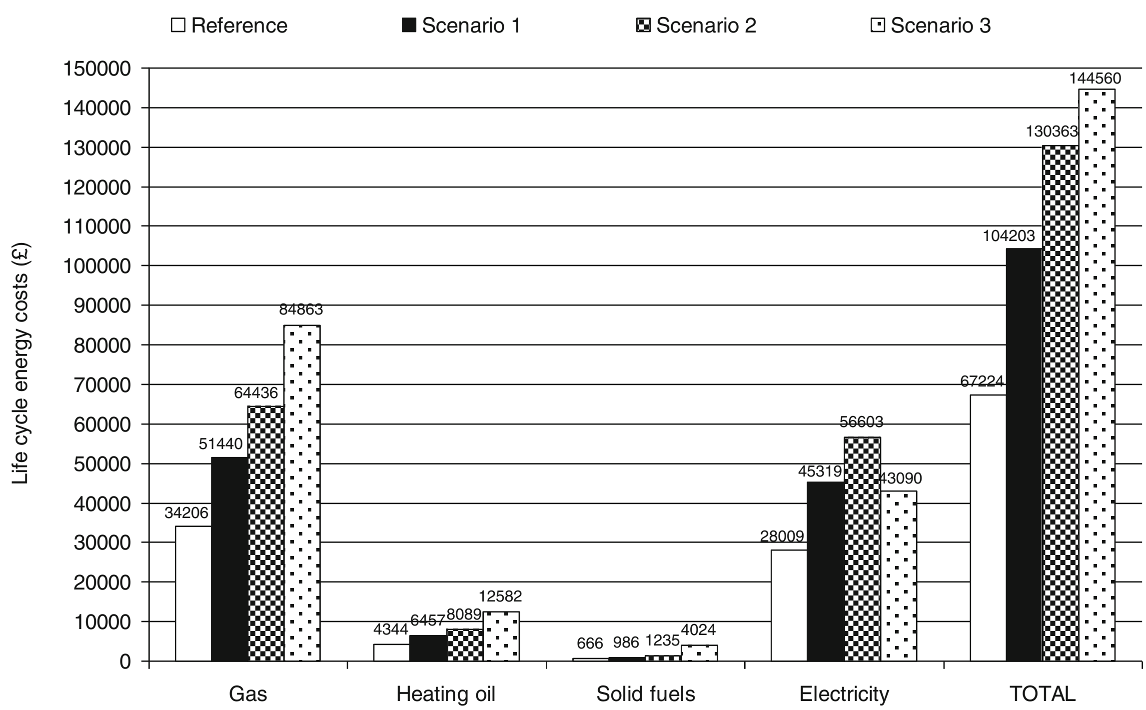

Fig. 10 Lifetime energy costs for the detached house for different scenarios

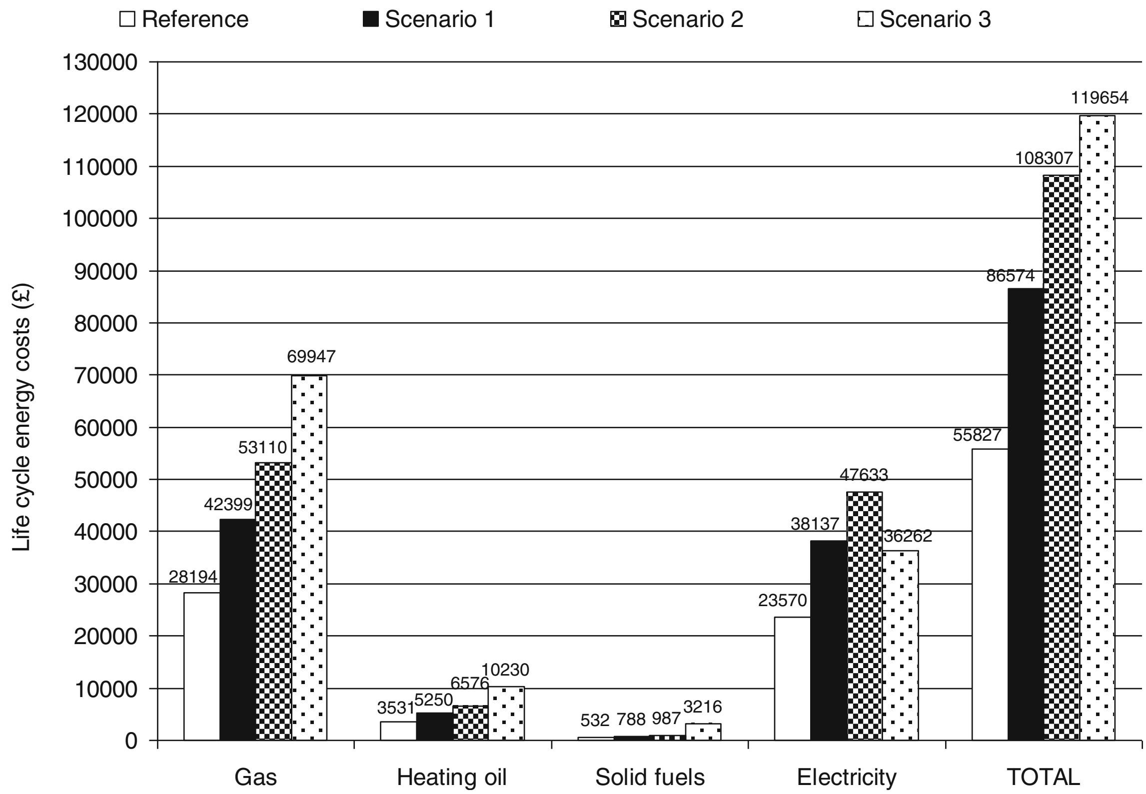

Fig. 11 Lifetime energy costs for the semi-detached house for different scenarios

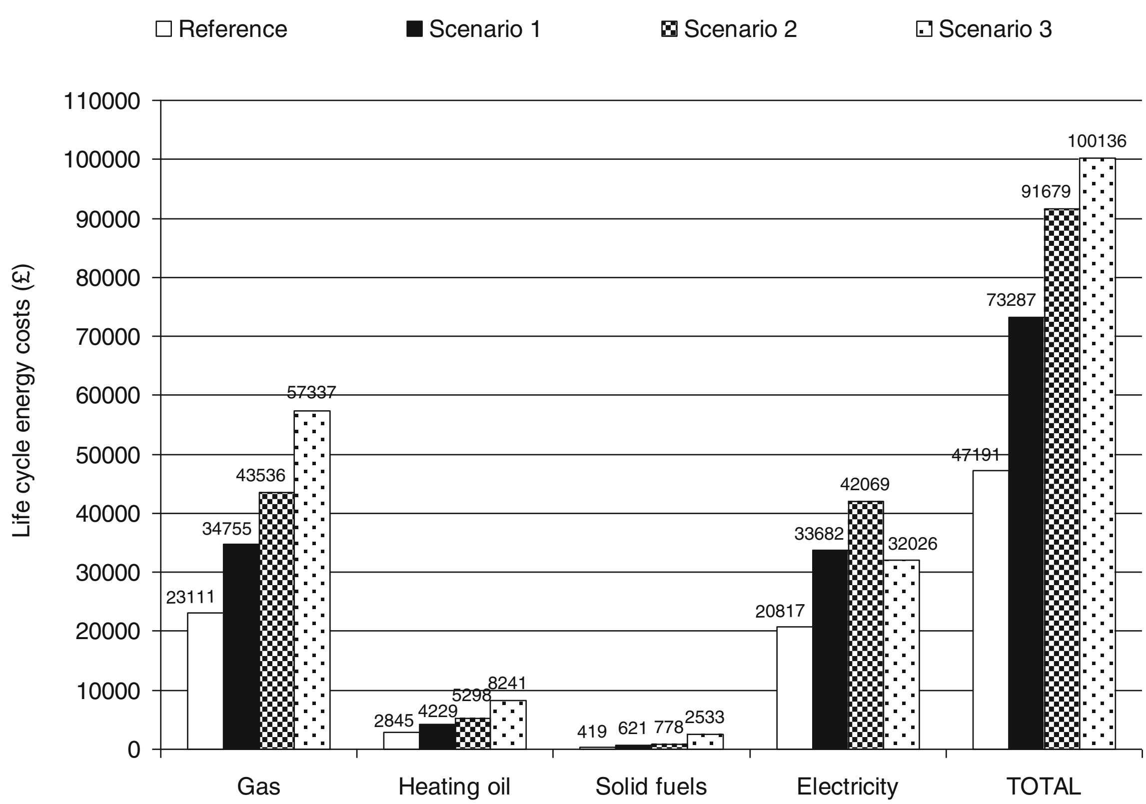

Fig. 12 Lifetime energy costs for the terraced house for different scenarios

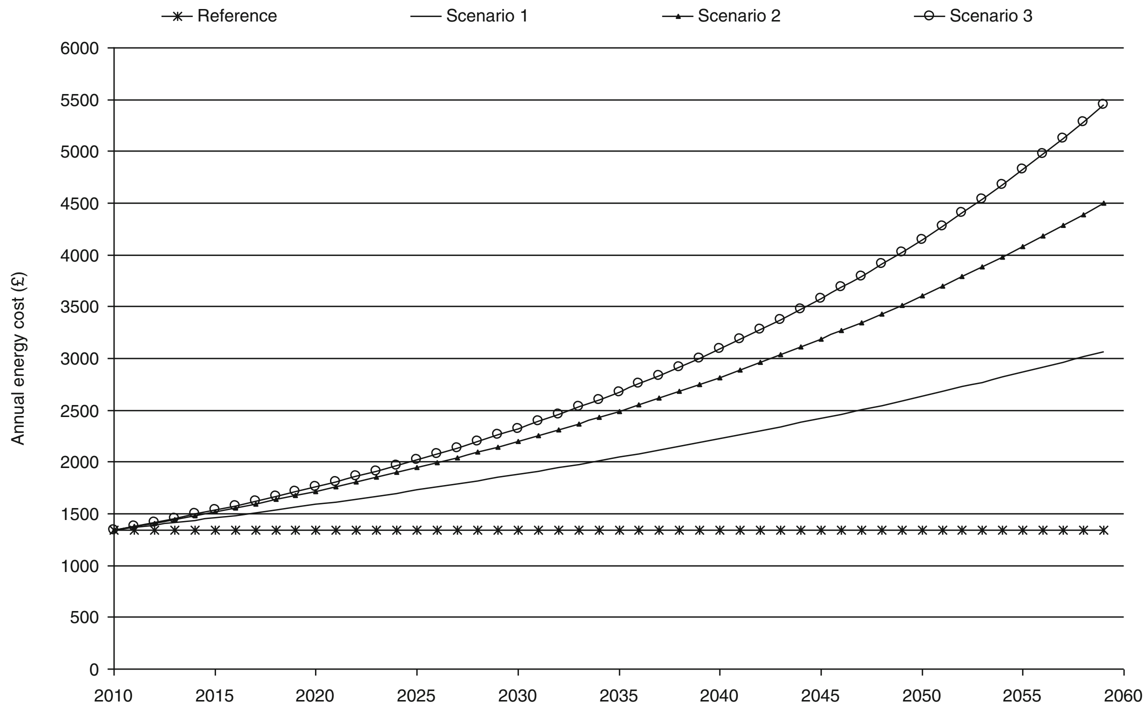

Fig. 13 Annual energy cost for the detached house over a service life of 50 years

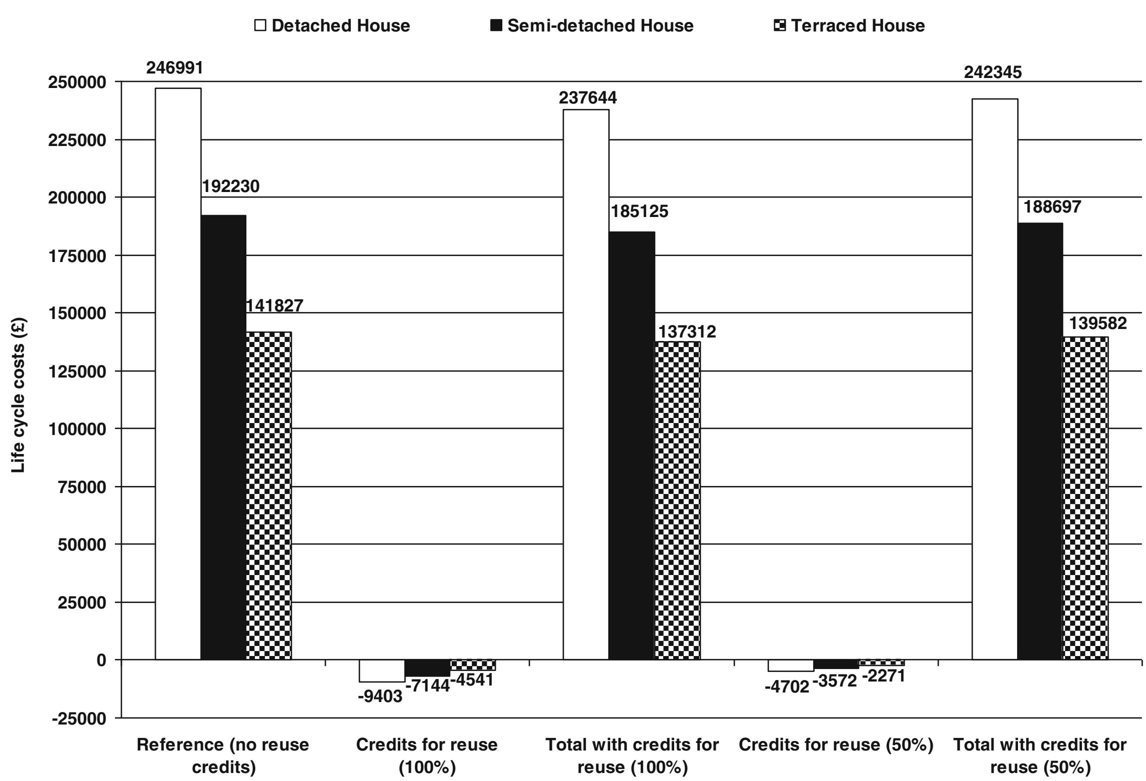

Fig. 14 Influence on the total life cycle costs of reusing the end-of life-materials. (Credits for reuse: 100 and 50 % represent respectively the percentage of costs recovered compared to the cost of the virgin materials. For the materials assumed to be reused, see Table 8; the costs of virgin materials are given in Table 3)

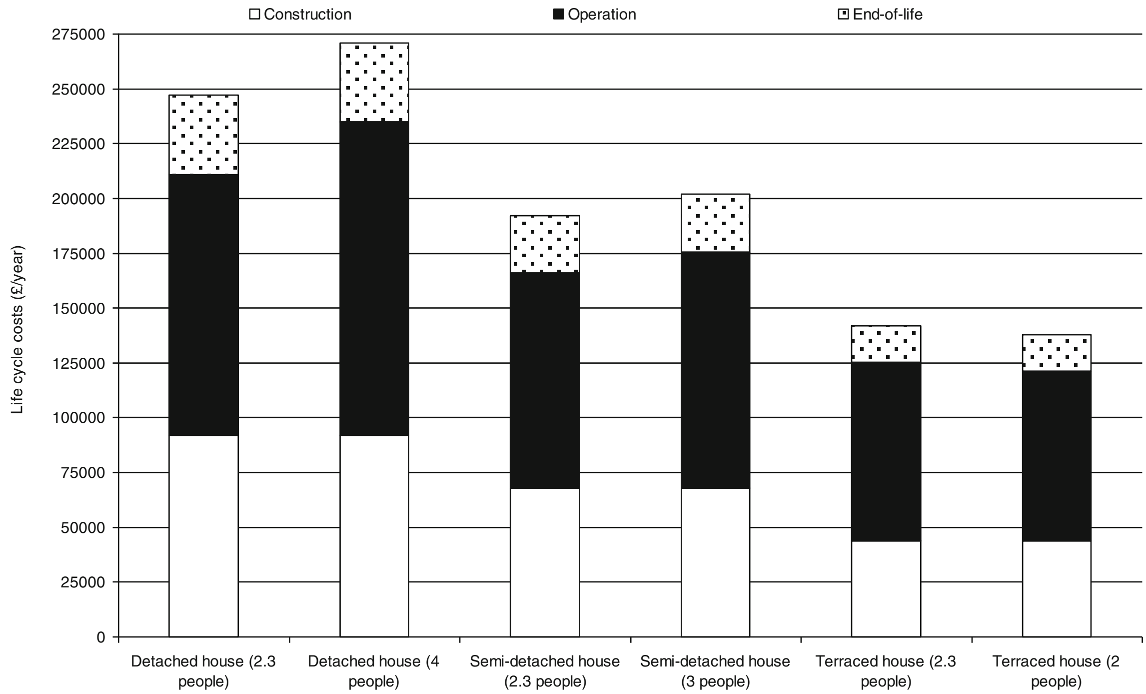

Fig. 15 Comparison of life cycle costs of a detached, semi-detached and terraced house for different number of occupants

the results for the detached house are shown). As indicated, scenario 1 is the best and scenario 3 the worst. According to the latter, by 2035 the energy bills could be two times higher than today and by 2050 they could triple. Thus, the impact on the total life cycle costs of houses would be significant, making it more difficult to eradicate fuel poverty of UK households.

3.5.2 Reuse of end-of-life materials

The influence on the total LCC of revenue from the reuse of the end-of-life materials is illustrated in Fig. 14. In the absence of real data, two scenarios are considered: one whereby the salvaged materials and components are sold back at the original

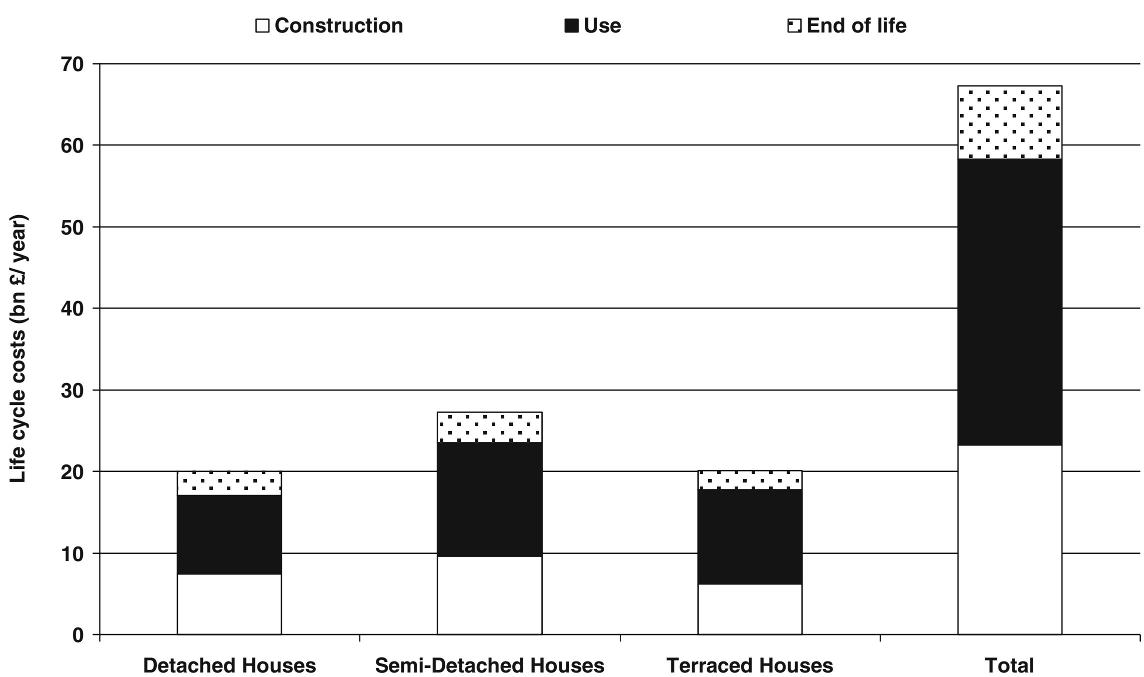

Fig. 16 Life cycle costs of the existing housing stock in the UK showing contributions from the life cycle stages

price of the virgin materials (see Table 3) and another where only 50 % of these costs are recovered. As indicated in the figure for the detached house, for example, around £9,400 can be recovered in the first scenario and a half of that in the second, reducing the total LCC by 3.8 and 1.9 % respectively. Thus, the influence of this parameter on the total LCC is insignificant.

3.5.3 Number of occupants

In this work, it has been assumed that all three houses have the same number of occupants (2.3 people), equal to the average size of the household in the UK. To find out how the number of occupants would influence the housing life cycle costs, a sensitivity analysis has been performed considering a theoretical number of occupants in each house based on their respective number of bedrooms, i.e. four people in the detached, three in the semi-detached and two in the terraced house.

These results are shown in Fig. 15 and indicate that the number of occupants has a relatively small influence on the life cycle costs of a house. This is mainly because space heating accounts for the large majority of the operational costs and this depends on the usable floor area of the house rather than the number of occupants. For example, the life cycle costs of a detached house occupied by four people increase by 10 % compared to the average household size of 2.3 people. For a semi-detached house with three people, the total life cycle costs increase by 5 % and for the terraced house, the costs are reduced by 3 % as the number of occupants is now lower (2) than originally assumed (2.3).

4 Life cycle costs of the existing housing stock in the UK

The LCC for the individual houses presented in the previous section have been extrapolated to the existing UK housing stock of seven million each of semi-detached and terraced and four million of detached houses (Utley and Shorrock 2008). The results in Fig. 16 indicate that the costs associated with the semi-detached houses are £27 billion per year while those of detached and terraced houses are £20 billion each. This gives a total of £67 billion per year or £3,364 billion over the 50-year lifetime. Although it is difficult to put these figures in context as there are no other comparable results, as an illustration, the UK's GDP in 2011 was £1.5 billion (World Bank 2012). Thus, the current housing sector is 'worth' annually around 45 times the GDP. Figure 16 also shows that around a half of the housing costs are generated during the use stage, of which around 50 % or £990 billion (over 50 years, at 2010 prices) is from energy use.

The high dependency on fossil fuels makes the housing sector vulnerable to future increase of energy prices. As shown in Section 3.5.1, the energy costs are likely to increase well beyond the optimistic assumption of constant energy prices made here and could triple to reach around £3,000 billion by 2050. This is likely to increase the fuel poverty of UK households further (DECC 2011b). Thus, in addition to improving energy efficiency, the housing sector will need to seek ways to become less dependent on fossil fuels and the volatility of energy prices. Some examples include installation of renewable technologies such as solar thermal panels, heat pumps and photovoltaics. However, this will require significant capital investments, pushing up the overall housing costs. These would need to be assessed carefully and balanced against the threat of the rising energy costs. The UK government has already introduced a range of incentives to stimulate installation of renewable technologies in the existing housing sector, including the Feed-in-Tariffs (FITs) (DECC 2012a) and Renewable Heat Incentives (RHI; DECC 2012b). However, due to a number of reasons, the uptake is still low providing less than 0.2 % of the final energy demand in the UK domestic sector (Balcombe et al. 2013; DECC 2012c). This is largely due to the initial investment required which is beyond the means of most UK households (Balcombe et al. 2013).

In addition to the FITs and RHI, the government has spent more than £30 billion on various measures to reduce fuel poverty over the last 11 years (2000–2011), including Winter Fuel Payments, Decent Homes and Warm Front while energy companies were expected to spend £3.9 billion over past 3 years (2008–2011) on energy efficiency and social assistance for households (Bolton 2010). This means that the government and industry have collectively spent on various fuel poverty measures 15 % of £220 billion spent by the householders on energy bills over the same period[1]—and yet six million households still live in fuel poverty, the same as in the 1990s (DECC 2009; Bolton 2010).

Thus, the government will need to seek further opportunities and options for reducing fuel poverty. This includes improving the uptake of renewable technologies but also incentivising householders to improve energy efficiency of homes through improved insulation, energy-efficient appliances and lighting, etc. For example, some estimates indicate that it would cost around £3,000 per house to improve the energy efficiency, typically through loft and cavity wall insulation or a condensing boiler (EST 2010). However, further measures and incentives will be needed to help reduce energy demand—while renewable technologies and fuel payments can certainly help towards reducing the dependency on fossil fuels and the costs of energy bills, it is the householders' behaviour that could have a much more significant impact on reducing the energy consumption and related costs.

[1] Calculated based on the annual energy costs given in Table 4 and extrapolated over 11 years for the total number of detached, semi-detached and terraced houses.

The next largest contributor to the life cycle costs is house construction, representing 35 % or £1,177 billion of the total housing costs. This is another issue affecting the residential construction sector as there is a stark difference between the construction costs and house market prices. The average house price reported in 2011 was £160,000 (HPUK 2012) while the average construction cost estimated in this study is £68,000. Thus, the average market price is around 2.4 times higher than the average construction costs, despite that fact that the latter already include developers' profits. This gap will deepen as the economy starts to recover and the house prices go up which, together with expensive mortgage products, will inevitably lead to a further decline in home ownership, particularly affecting the prospects of young people to purchase a home. Therefore, unless appropriate measures are taken by the government and other players in the construction sector, there is a danger of turning a basic human need—shelter—into a luxury commodity.

5 Conclusions

The total house life cycle costs over the 50-year lifetime range from £247,000 for the detached to £142,000 for the terraced house. Half of the costs are from the use stage of which around 50 % is due to the costs of energy. This is mainly because of the use of gas for space and water heating and electricity costs. The average annual energy costs per household are estimated at £1,135. If the energy costs continue to grow as expected, in 2035 the energy bills could be twice as high and in 2050 they could triple. Thus, the impact on the total life cycle costs of houses would be significant, making it more difficult to eradicate fuel poverty of UK households.

The construction costs contribute 35 % to the total LCC of with the walls and the roof being the most expensive items. The remaining 13 % of the costs are incurred at the end of life of the house which are largely (85 %) due to the cost of labour for demolition. Recovery of end-of-life materials has a limited potential to reduce the overall life cycle costs of a house.

At the sectoral level, the total life cycle costs of housing are estimated at £67 billion per year with semi-detached houses contributing £27 billion, followed by the detached and terraced houses with £20 billion each. Over the 50-year lifetime, the total life cycle costs add up to £3,364 billion.

The existing housing stock in the UK is facing a number of challenges that will need to be addressed in the near future. These include improving energy efficiency through better insulation and use of energy-efficient appliances and lighting, which would reduce energy bills but also environmental impacts. Furthermore, reducing the dependency on fossil fuels could help to reduce both fuel poverty and environmental impacts. Moreover, the disparity between the construction costs and house market prices will need to be addressed to ensure that access to and house ownership do not become the privilege of a few.

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